Article

Influence of site index on the growth of *Pinus patula* Schltdl. *et* Cham. plantations

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Abstract

The objective of this study was to evaluate the influence of the site quality on the growth and increase of a *Pinus patula* plantation in *Ixtlán de Juárez*, *Oaxaca*. In a plantation established in 1995, there were thirty 400 m^2 sites systematically distributed for carrying out a forest inventory of the trees. Dendrometric variables were measured and growth cores were extracted from two dominant trees at each site in order to obtain the mean annual increment (MAI), the current annual increment (CAI) and the ring width in the early and late wood. With data on the height and age of trees from the plantation and natural forest, functions were adjusted to estimate the site index (SI) by using the curve method with a baseline age of 40 years. Analysis of variance was performed using site qualities as a classification variable, and the increase in early and late wood was estimated by means of regression models. The quality of the site influences the dasometric and growth variables in *P. patula* (p = 0.0001). In addition, the total ring width for a low and an excellent SI was found to be 5 and 8.85 mm, respectively. Increases in early and late wood are positively correlated with the site quality (p = 0.0001). Therefore, the specific gravity of the wood is lower in higher quality sites. The optimal growth for the early and late wood varies in relation to the site quality. The increase and growth of *Pinus patula* is determined by the site quality.

Key words: Guide curve, specific density, site index, late wood, early wood, *Pinus patula* Schiede ex Schltdl. *et* Cham.

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Introduction

Today, having reliable information about the quality of the forest areas where plantations are established for business purposes, especially those of rapidly growing species like *Pinus patula* Schltdl. *et* Cham., is a necessity, as there is a close relationship between the environmental variables and the yields. Therefore, a characteristic of the tree must be assessed in order to visualize the influence of all the agents that determine the productivity of a particular area; the assessed characteristic is usually the dominant agent (Arteaga-Martínez, 2000). In this sense, forest management focuses on the quality of the site where a *taxon* grows in order to arrange the stands according to its productive potential (Esse *et al*., 2007; Torres-Rojo and Valles-Gándara, 2007). In the terminology of forestry, the season's quality refers to the ability of a specific area to sustain tree growth, and it is assessed using an index known as site index (SI), which is expressed in terms of the maximum height reached by the dominant and co-dominant trees in a stand at a given time (baseline age) (Cornejo *et al.,* 2005; Vargas-Larreta *et al.,* 2010).

According to Ugarte-Guerra and Domínguez-Torrejón (2010), the magnitude of the tree growth is a function of the potentialities defined by their genotype, whose level of expression is influenced by the condition of the site (Davel and Ortega, 2003). Based on this, Martínez-Salvador *et al.* (2013) point out the importance of learning the impact of environmental factors on growth and productivity in forest plantations, as these are an alternative for obtaining goods and services in the short term, especially for meeting the high demands of the timber industry (Pérez *et al.,* 2012; Martínez-Zurimendi *et al.,* 2015).

The literature includes a large number of researches assessing the site quality of various forest species with the use of mathematic models or by relating it to an environmental variable. However, very few papers address the influence of the site quality on tree growth or its repercussions on certain wood anatomical variables.

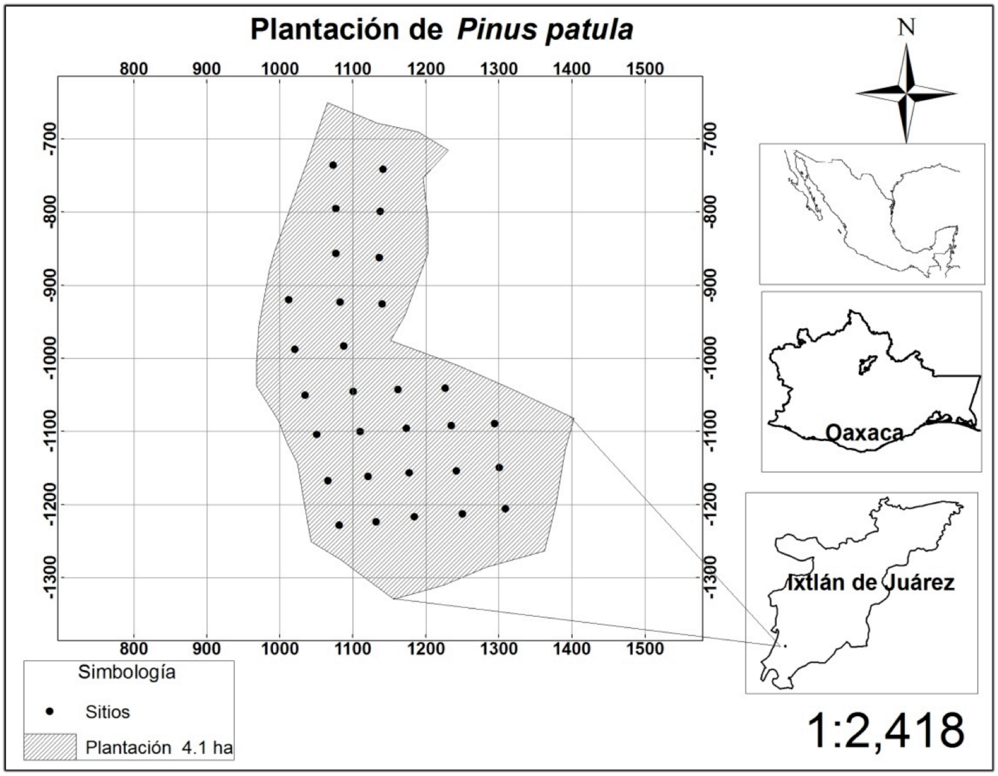
Various authors base their assessments on mathematical-statistical models and have obtained high determination coefficients (Cornejo *et al.,* 2005; Hernández-Ramos *et al.,* 2014; Rodríguez-Carrillo *et al.,* 2015). González *et al.* (2013) assessed the different site quality classes in *Pinus caribaea* var. *caribaea* Morelet in Cuba, based on the soil variables; their model accounted only for 30 % of the variation in site quality. Davel and Ortega (2003) estimated the SI using 12 environmental variables, and they obtained a model that explains 67 % of the total variation.

Studies of the site quality evaluate only the maximum yields of an area; they include no research on their influence upon the specific density of the wood, ring width, or increases in the early and late wood –all of which are variables of interest for the industry, as both the processing and the final quality of their products are dependent upon them (León, 2010). In order to document these aspects in the present study, we decided to evaluate the influence of the site quality on the increase and growth of a *Pinus patula* plantation in *Ixtlán de Juárez*, *Oaxaca*.

Materials and Methods

Study area and sampling

The research was carried out in a 4.1 hectare *Pinus patula* plantation located 12 km northeast of *Ixtlán de Juárez*, *Oaxaca*, at the coordinates 17°22’38.69’’ N and 96°28’44.8’’ W, and at an altitude of 2 550 masl. The climate is C(w_2), subhumid temperate; the precipitation ranges between 900 and 1 100 mm per year, and the mean annual temperature is 20 °C (Figure 1). The plantation was established in 1995, on plots with a 16 to 42 % slope. No thinning has been carried out since 2010, and the tree density ranges between 400 and 1 100 trees ha^{-1}; therefore, there is an overlap of tree crowns (Rodríguez-Ortiz *et al.*, 2011).



Plantación de *Pinus patula* = *Pinus patula* plantation; Simbología = Symbology; Sitios = Sites; Plantación = Plantation.

Figure 1. Location of the *Pinus patula* Schltdl. *et* Cham. plantation in *Ixtlán, Oaxaca*.

Based on a systematic sampling, thirty circular temporal sites with a surface area of 400 m^2 were distributed. The following variables were measured in all the trees in each site: normal diameter (ND, in cm), with a measuring tape (Bioweb^{TM} JIMG-59571); total height (m), with a Haga altimeter (GmbH & Co D-90429); crown diameter (CD, in m), with a Truper^{TM} measuring tape. Two diameters and the sociological position of the crowns were considered. Other data recorded were: altitude (m) and exposure, measured with a Garmin e Trex 10 GPS, and slope (%), with a Finland Pm5/360pc Suunto clinometer. A shaving was extracted from two dominant trees, at a height of 1.30 m, using a Pressler drill; the methodology described by Quiñones *et al.* (2015) was then applied to the analysis of the growth variables.

Analysis of the shavings

A total of 60 shavings were processed in order to calculate the mean annual increase (MAI, in mm year^{-1}) and the current annual increase (CAI, in mm year^{-1}) in diameter; their age was estimated by counting the total number of rings from the core to the bark; the end and middle diameters (in cm) and the total length (in cm) were also measured. Marks were made, using the viewfinder of an Optika^{TM} SZ-CTV stereoscope, to differentiate between the early and late wood of each ring; the length (mm) and diameter (mm) of these were measured using a TITAN^{TM} electronic digital caliper and their volume was subsequently calculated with Newton's dendrometric formula (Romahn and Ramírez, 2006). The shavings were placed in a Memmert^{TM} drying oven UFP800DW at a temperature of 100 °C until they reached a constant weight; the dry weight (Dw, g) was then estimated, using a (SHIMADZU^{TM} ATY224) analytic scale. Based on the volume and the dry weight, the specific density of the wood was determined using the following equation:

$$SD = Dw/V$$

Where:

SD = Specific density (g cm^{-3})

V = Volume (cm^{3})

Dw = Dry weight (g)

Analysis of the information

Normality and variance homogeneity tests were carried out, using the UNIVARIATE procedure and the Shapiro-Wilk and Bartlett tests, in order to meet these assumptions. The square-root transformation (*SQRT-x*) was applied to those variables that failed to meet them.

The SI model was built based on 90 shavings collected within the plantation and in the adjoining natural forest, exhibiting all of the growth conditions of *P. patula*. The data of the height and age obtained by analyzing the shavings were used to adjust functions for estimating the site index (Montero and Kanninen, 2003; López and Valles, 2009; Pérez *et al.,* 2012; Rodríguez-Carrillo *et al.,* 2015). The statistical package SAS (SAS, 2004) was used, together with the minimum squares method and the MODEL procedure, for the regression analysis routine. The best adjusted model turned out to be the one by Schumacher:

$$SI = 40.33e^{-13.52(1/age)}$$

Where:

SI = Site index (m)

e = 2.7182

The following statistics support the adjusted function: adjusted determination coefficient (R^2 adj)=0.94, the error mean square (EMS)=4.98, and the standard error (SE)=2.23. SI curves were built using the guide curve method with a baseline age of 40 years; this entailed adjusting the average tendency of the dominant heights across the entire age interval in order to obtain a curve known as guide curve, which was used to build a family of curves above and below it, each representing a different site quality during the period (Attis *et al.*, 2015).

In order to observe the optimal growth momentum in the early and late wood variables, the intersection of the MAI and the CAI was charted. The equations were assessed using the following goodness-of-fit statistics: significance, adjusted determination coefficient (R^2), mean square error (MSE), variation coefficient (VC) and residual statistics.

The various site qualities were grouped according to the SI, as low (IS≤24 m), fair (IS>24, ≤27), good (IS>27, ≤30), very good (IS>30, ≤33) and excellent (IS>33). In order to compare the behavior of the dasometric and growth variables in relation to the site quality, variance (p=0.05) analyses were carried out, using the site quality as a classifying variable, and Duncan's means (p=0.05) separation test, for observing the differences.

Results and Discussion

Effect of the site quality

The dasometric and growth variables of the trees were highly significant (p≤0.0001); *i.e.* the behavior of the assessed variables was different in regard to the site quality (Table 1). This agrees with the findings of Martínez-Salvador *et al.* (2013), who, having assessed the productivity of three season's qualities for *Pinus arizonica* Engelm. and *P. engelmannii* Carr. in *Chihuahua*, registered significant differences (p<0.05) between their effects on the productivity of the trees. On the other hand, Mollinedo *et al.* (2005) proved that the sites with the highest productivity form clusters in settings with the best season's qualities (Jerez-Rico *et al.,* 2011).

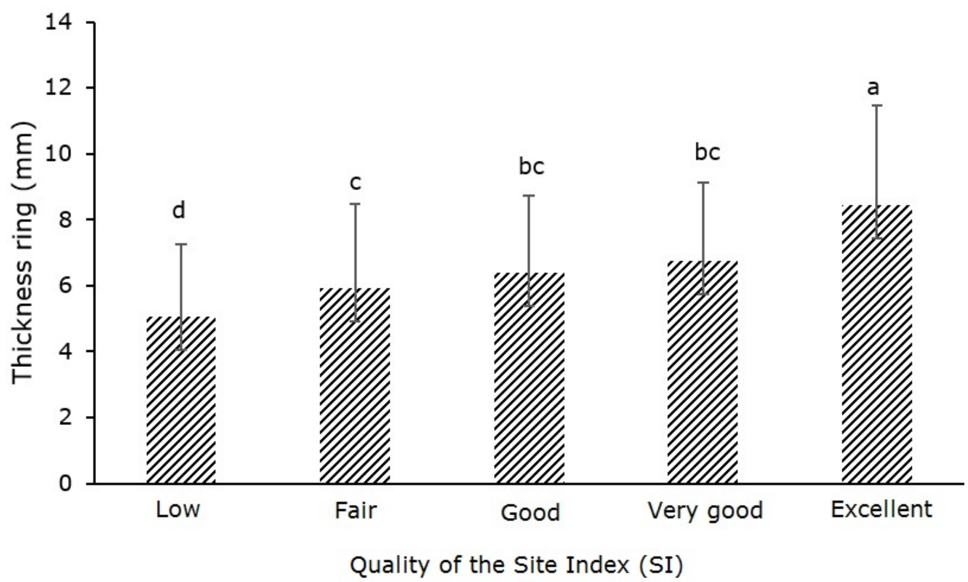
Table 1. Effect of the site quality on the dasometric and growth variables in *Pinus patula* Schltdl *et* Cham.

VS	DF	ND (cm)	Height (m)	TD (trees ha^{-1})	SD (g cm^{-3})	Early wood MAI (mm year^{-1})	Early wood MAI (mm year^{-1})	Late wood MAI (mm year^{-1})	Late wood MAI (mm year^{-1})	ART (mm)
		SM								
CS	4	18.26**	31.47**	474.83**	0.08**	0.41**	0.38**	7.56**	7.96**	7.06**
Error	1255	0.21	0.01	13.54	0.002	0.01	0.04	0.05	0.18	0.23
Total	1259									

The values of the mean squares are raised to the square root; **= Highly significant ($p \leq 0.01$); ND= Normal diameter; TD= Tree density; SD= Specific density of the wood; MAI= Mean annual increase; CAI= Current annual increase; ART= Annual ring thickness; SQ= Site quality (excellent, very good, good, fair, and low); VS= Variation sources; DF= Degrees of freedom; CM = Square means.

The relationship between the ring thickness and the site quality was positive, i.e. the better the season's quality, the thicker the ring. For example, in sites with an excellent site quality, the ring thickness is 8.45 mm, whereas in those with a low quality, it is equal to 5 mm (Figure 2); these measures are statistically different (p= 0.0001). In rapidly growing species like *Pinus patula*, it is important to determine the ring thickness for each type of SI, because this makes it possible to determine the speed at which the normal diameter variable increases (Melandri *et al.*, 2007).

According to the findings of this research, the site quality influences the ring thickness; this is as cited by Goche-Télles *et al.* (2003) for two site qualities (low and high) in *Pinus patula* forests of the physiographic province of the Eastern *Sierra Madre*; these authors point out significant statistical differences (p=0.0001), and they attribute these differences in growth to the conditions under which the species develops; tree growth depends to a great extent on the properties of the soil, provided that the climate conditions are uniform (Afif *et al.*, 2010). Moya *et al.* (2010) studied the influence of the physical and chemical properties of the soil on the quality of the wood of *Tectona grandis* Linn F., and they claim that these properties also have an impact on tree growth.



The vertical lines represent the standard deviation; different letters above the bars correspond to statistical differences (Duncan, 0.05).

Figure 2. Annual ring thickness in relation to the quality of the SI.

The specific density of the wood is one of the main criteria for determining its quality because it is directly related to its resistance and to its pulp yield for the paper industry (Daniel *et al.*, 1982; Monteoliva *et al.,* 2002). In forest plantations, it is important to monitor the specific density of the wood, as this variable can serve as a basis for determining the quality of the timber products offered by the industry.

This study shows that the highest values for specific gravity correspond to sites with a fair or good quality (0.37 and 0.36 g cm^{-3}, respectively), while the excellent and very good site qualities have lower values (0.33 and 0.32 g cm^{-3}) (Figure 3). This suggests that there is no definite pattern; therefore, trees located in sites with a better (very good and excellent) season's quality exhibit a more active growth and develop wood with a lower specific gravity. Nevertheless, low quality also exhibited a low specific gravity, which can be accounted for by the fact that the site quality is the combination of several factors, including climate, soil, physiography, and management; a variation in a greater or lesser degree can result in a heterogeneous growth because the trees are located in sites with different season's qualities (Table 2) (Mora *et al.*, 2015). Furthermore, a low specific density of the wood –*i.e.* between 0.32 and 0.37 g cm^{-3}– is caused by the youth of the trees, whose age is 21 years, and by the fact that the walls of the cells of the stem have not yet grown much in thickness (López and Valencia, 2001). This would account for the obtainment of lower values than those cited by Vázquez-Cuecuecha *et al.* (2015) –a basic wood density of 0.46 g cm^{-3} in mature *Pinus patula* trees– in relation to the properties of the soil. Goche *et al.* (2011) agree on the same value (0.46 g cm^{-3}) in *Pinus patula* trees. However, they argue that the density of the wood varies within the various parts of the tree, between individuals, and between species, and that it may be influenced by the age, shape, genetic differences, growth speed, and evolution of the tree (Jovanovski *et al.,* 2005; Castillo *et al.,* 2013).

From an industrial point of view, in order to help avoid speculations, the specific density of the trees from forest plantations must be uniform because it has an influence on the quality of the final product (Silva-Arredondo and Návar-Cháidez, 2012).

Table 2. Characteristics of the *Pinus patula* Schltdl. *et* Cham. trees in relation to the quality of the site where they grow.

Quality of the SI	TD* (trees ha^{-1})	ND* (cm)	Height* (m)	CD* (m)
Low	820.11 ± 232.76 b	26.02 ± 4.37 d	22.65 ± 1.33 e	4.59 ± 1.13 d
Fair	769.04 ± 180.61 c	29.10 ± 4.79 c	25.79 ± 0.74 d	5.19 ± 1.16 c
Good	758 ± 223.14 c	31.27 ± 5.48 b	29.1 ± 0.89 c	5.75 ± 2.34 b
Very good	982.67 ± 185.09 a	31 ± 7 b	31.83± 0.90 b	5.61 ± 2.59 b
Excellent	649 ± 11.13 d	38.5 ± 1.51 a	34.5 ± 0.50 a	9.1 ± 1.92 a
VC	25.42	17.2	3.76	31.15

The values correspond to the mean and its respective standard deviation. Different letters by column indicate statistical differences (Duncan, 0.05); SI = Site index; TD = Tree density; ND = Normal diameter; CD = Crown diameter; VC = Variation coefficient. * = p = 0.0001.

The vertical lines represent the standard deviation; different letters above the bars correspond to statistical differences (Duncan, 0.05).

Figure 3. Specific density in relation to the quality of the SI.

The MAI and CAI have a rising behavior in relation to the site qualities, i.e. the increases in early and late wood are larger as the quality improves. For example, the early wood MAI for a low quality was 3.7 mm year^{-1}, while for an excellent quality it was 6.76 mm year^{-1}; both qualities were significantly different (Duncan, 0.05) (Table 3). This may be due to the fact that the trees that grow in sites with better season's qualities have larger crowns and generally form the upper canopy and therefore capture more sunlight (Interián-Ku *et al*., 2014) (Table 2). In this sense, as the season's quality diminishes, the resources will be more limited, and this will be reflected in the growth dynamic of the tree (Mayo *et al.*, 2008).

Table 3. Mean annual increase (MAI) and current annual increase (CAI) of the early and late wood in relation to the quality of the SI.

Quality of the SI	Early wood		Late wood	
	CAI* (mm year^{-1})	MAI* (mm year^{-1})	CAI* (mm year^{-1})	MAI* (mm year^{-1})
Low	3.70 ± 1.74 d	3.70 ± 0.96 e	1.35 ± 0.50 c	1.35 ± 0.25 d
Fair	4.40 ± 1.91 c	4.40 ± 0.84 d	1.51 ± 0.59 b	1.51 ± 0.30 bc
Good	4.81 ± 1.70 c	4.81 ± 0.83 c	1.55 ± 0.59 ab	1.55 ± 0.36 b
Very good	5.28 ± 1.82 b	5.28 ± 1.39 b	1.44 ± 0.50 bc	1.44 ± 0.22 c
Excellent	6.76 ± 2.00 a	6.76 ± 0.57 a	1.69 ± 0.72 a	1.69 ± 0.36 a
VC	41.04	21.24	38.35	20.37

The values correspond to the mean and its respective standard deviation.

Different letters by column indicate statistical differences (Duncan, 0.05). SI= Site index; CAI= Current annual increase (mm year^{-1}); MAI= Mean annual increase (mm year^{-1}); VC= Variation coefficient. *= p = 0.0001

Growth estimation in early and late wood

The intersection between the CAI and the MAI shows the precise time at which the increases are optimal, that is, when the tree attains its best timber yield (Martínez *et al.,* 2014). Sites differing in season's qualities exhibit optimal increases at almost the same time (for a low quality, at the age of 8 years, and for an excellent quality, at the age of 9 years); this indicates a similar behavior of both. However, the increases of early wood in sites with an excellent quality were of 9 mm, but only of 5 mm at low quality sites (Figure 4). In this regard, Pompa-García and Domínguez-Calleros (2015) point out that the good ecological capacities of a site have a positive impact on tree growth.

The specific density of the late wood is important because it influences the proportion of dry wood per volume unit; thus, if the percentage of late wood increases, so does the wood density (Pereyra and Gelid, 2002). The age at which *Pinus patula* registered its optimal yield for this variable was 8 years, with almost 2.4 mm for an excellent site quality, whereas at the age of 10 years in a low site quality, the yield was merely of 1.5 mm (Figure 5). This may be due to the fact that the trees exhibit different growth strategies in terms of the environment in which they grow. Therefore, the proportion of late wood will depend on the variations of the site (Cambrón *et al.,* 2013; Piraino, 2016). The forest manager must adequately identify the site where the plantation of this species will be established in order to ensure a uniform behavior of the trees.

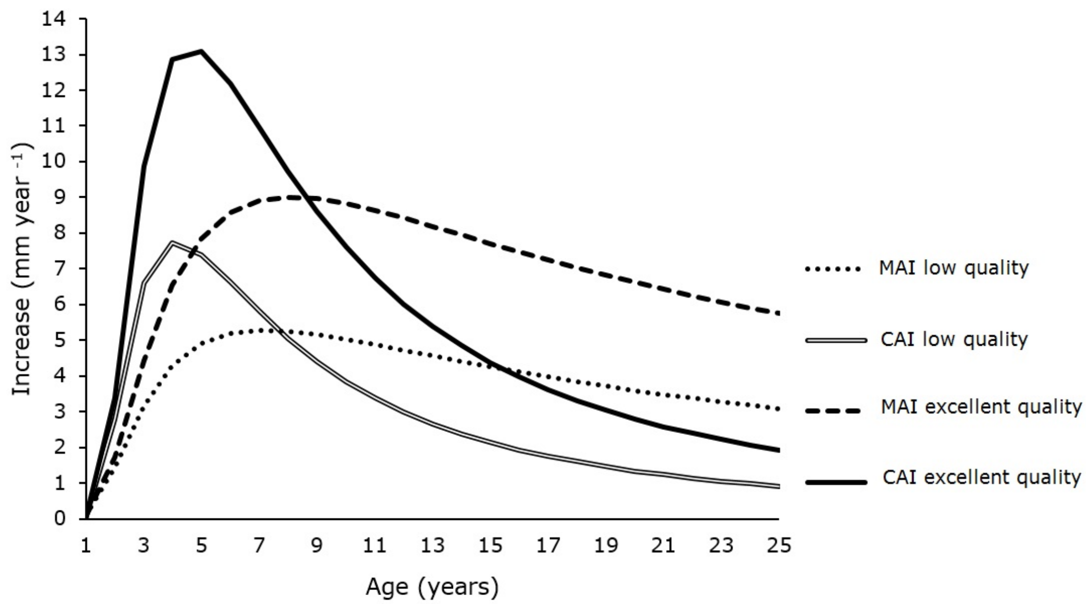


Figure 4. Contrast between the early wood increases in relation to the site qualities.

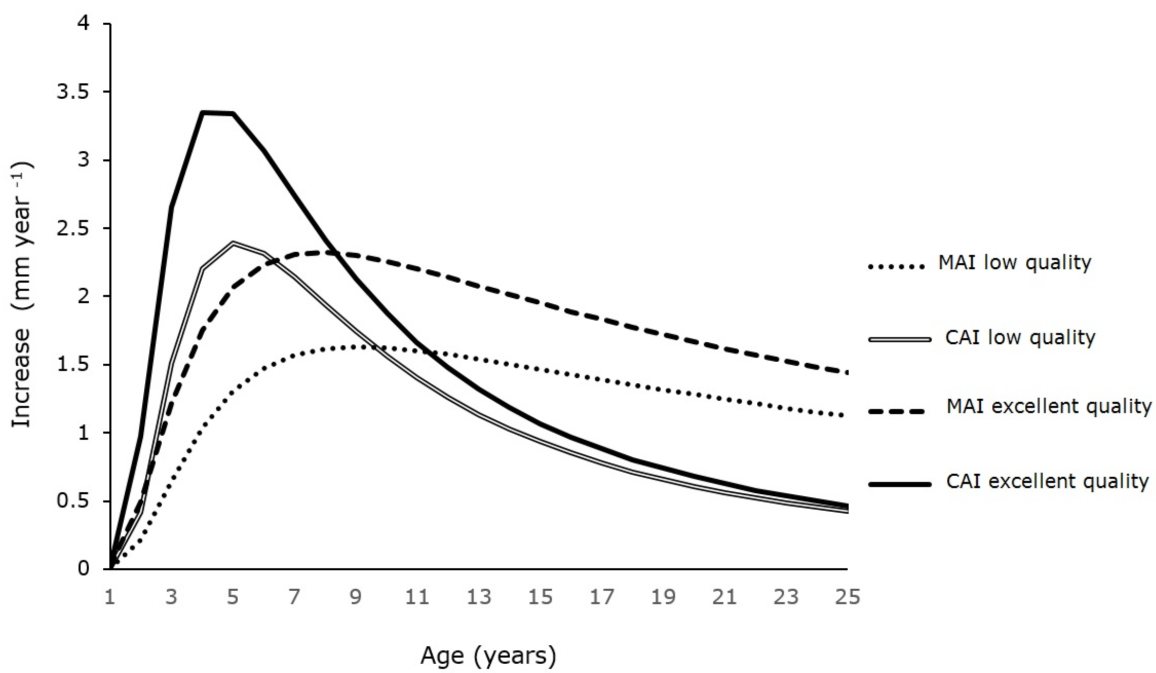


Figure 5. Contrast between the late wood increases in relation to the site qualities.

Conclusions

The increase and growth of *Pinus patula* in a plantation is determined by the site quality ($p=0.0001$). When the environmental factors are favorable, the increases of early and late wood reach levels of 6.76 and 1.69 mm year^{-1}, respectively. However, trees growing in sites with a better season's quality, and therefore with a more active growth, form wood with a lower specific density (0.33 and 0.32 g cm^{-3}) than those located in sites with a less favorable season's quality (0.37 and 0.36 g cm^{-3}).

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Conflict of interests

The authors declare no conflict of interests.

Contributions by author

J. Ángel García-Aguilar: in-field sampling; Vicente Arturo Velasco-Velasco and Gerardo Rodríguez-Ortiz: statistical data analysis; José Raymundo-Enríquez del Valle: laboratory tests.